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Interpersonal differences in the friction response of skin relate to FTIR measures for skin lipids and hydration

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ABSTRACT

Understanding the mechanical response of skin to contact is of importance when developing products that interact with the skin. The shear forces that arise due to friction in the interface are a key aspect of skin interactions, because shear is known to contribute to discomfort and tissue injury. However, the frictional response of skin shows large variations between people. It has been hypothesised that these variations relate to differences between people in the physiological properties of their skin, but the underlying mechanisms are not well understood. In order to gain new insights into these interpersonal differences in friction behaviour, in vivo FTIR measurements and in vivo friction measurements were performed on the same patch of skin. Quantitative analysis of the various peaks in the FTIR spectra provided information on the moisture content of the stratum corneum and the amount and mechanical properties of the lipids on the skin. The lipid viscosity, as characterised by the width of the 2920 cm^{-1} peak, correlates with the friction, whilst, interestingly, no relationship was found between the quantity of lipids on the skin surface and the coefficient of friction. Additionally, and as expected, a fairly strong correlation was obtained between the moisture content, as characterised by the height of the Amide I peak and the coefficient of friction. The presented results show that spectroscopy techniques can be used in as a non-invasive method to identify people who may show elevated levels of friction and thus are at increased risk of developing shear induced tissue injury.

1. Introduction

The human skin forms the mechanical interface with the world around us and through contact between the skin and objects humans can sense, perceive, handle and manipulate items. Understanding the forces that act on the skin during contact, particularly those in the lateral (or shear) direction, is of importance in the development of products that interact with skin, such as textiles, clothing, sports equipment, grab rails and handle bars as well as medical devices and prosthetics. In many cases the forces related to shear are essential for the appropriate operation of the product, including providing grip or enabling smooth, non-jittering sliding. However, shear forces are also known to cause discomfort [1,2] and may result in tissue injury [3–5]. The shear forces are governed by the friction behaviour of the contact, either static or dynamic, which is the result of a complex interplay between the surface properties and the material properties of both the skin and the contacting object, the local environment, as well as the operational parameters such as the contact pressure and the sliding velocity.

It is well established that there are large differences between individuals regarding the friction behaviour of skin [6–14], meaning that the friction measured on the same skin site on different people under identical operational conditions shows a large variation [6,15,16]. The underlying cause lies within the many physiological parameters that are linked to the characteristics of the skin and the variation of these parameters between people. Research into the tribological properties of the skin has focused on establishing relationships with the geometrical and the mechanical characteristics of the skin [17], the hydration or moisture content of the stratum corneum, the uppermost layer of the skin [6–9], the presence of substances such as sweat, sebum and specific surface lipids [10], as well as gender, age and ethnicity [8,9,11–14]. An excellent overview of the observed trends was provided by Derler [18], but at present a full understanding of the predominant mechanisms involved in the skin's response to shear forces is still lacking.

An additional complicating factor to studying the interaction behaviour of the skin is that the process of measuring and quantifying the moisture content of the skin and the amount of sebum on the skin is not straightforward or unambiguous [19,20] and may also interfere with

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the friction test. The moisture content of the skin can be measured by assessing the capacitance of the stratum corneum and is typically expressed in arbitrary units [19]. Kwiatkowska [21] reported a strong correlation between the capacitance measurement and the friction for a single subject, although a clear quantitative relationship was not established. Gerhardt [7] mentions a linear correlation between friction and capacitance based moisture content for each individual in their experiment, but also showed that no correlation was observed when collating the results obtained on all subjects, meaning that a moisture measurement based on capacitance does not have a general predictive value with respect to the friction behaviour. Measuring the sebum quantity on the skin involves the removal of sebum by means of an absorption tape that subsequently becomes translucent. A photometric method is then employed to measure the transmittance of light though the tape, which can be correlated to the sebum quantity [20]. However, applying absorbent tape causes (partial) removal of the lipid layer, which would introduce deviations in the obtained friction results when performed before the friction test. Performing the sebum collection after the friction experiments would also be an issue as the skin might respond to the previous interaction by replenishing and releasing additional sebum during the hour-long collection period.

Based on the evidence provided in the literature, it can be concluded that large interpersonal differences are observed in the shear and friction behaviour of the skin and that these have been linked to the characteristics of the skin, but that an accurate and repeatable characterisation and quantification of skin properties is currently hindered by the employed measurement methods. In this work we aim to use Fourier Transform Infrared Spectroscopy (FTIR) to characterise the skin. FTIR has previously successfully been employed to assess the moisture content of in-vivo skin [22–26] as well as to characterise the sebum layer [23]. As the output signal of an FTIR measurement is directly related to the number of molecular bonds, it can provide a direct measure of both sebum and moisture quantity. Furthermore, the FTIR measurement can be performed in vivo and does not require the removal of the sebum layer.

1.1. The response of skin to shear loading

The shear stresses that occur in the skin as the result of interaction with a counter body are the result of forces due to what engineers call *static friction* and clinicians tend to refer to as '*shear*', between the two bodies in contact. It is important to distinguish these from forces due to rubbing, or dynamic friction forces, which are important aspects in case of abrasions and friction burns. Both are commonly referred to as 'friction' and result in shear stresses acting on the surface. Friction is the result of dissipative processes that occur in the interface between the two contact partners, which includes breaking any intramolecular or adhesive bonds between the surfaces, as well as deformation and hysteresis in the materials.

It has long been established that friction is a system property, that not only depends on both surfaces in a contact, but also on the conditions occurring in the contact, such as the contact pressure, temperature and humidity [27]. A common method of quantifying the friction in the contact is the coefficient of friction, which is the ratio between the (resulting) lateral or friction force F_F and the (applied) normal force F_N. The friction force can be divided into an adhesive component $F_{F,A}$ and a component related to deformation processes, such as ploughing and hysteresis $F_{F,D}$. These two components can be assumed to be independent from each other [28], and previous research [16,28,29] suggests that for skin under a wide range of conditions the adhesive component is dominating the total friction force, meaning the deformation component may be ignored. The adhesive component of the friction force can be defined as the area of contact between the two interacting surfaces (A_{real}) multiplied by the shear strength of the interface between the two materials (τ) [28]. These considerations are captured in Eq. 1:

$$F_F = F_{F,A} + F_{F,D} \approx F_{F,A} = \tau \bullet A_{real} \quad (1)$$

Eq. 1 essentially means that the friction in a skin-product interface relates to a combination of parameters that determine the size of the contact (A_{real}) and an interface parameter τ determining the resistance against shear of that contact. Variations in the geometry and topology of the layers of the skin, as well as any differences in mechanical properties due to e.g. the moisture level of the skin or any absorbed substances will affect the real contact area, whilst variations in substances present on the surface of the skin, such as grease, soap, dirt, topical creams and lipids, will affect the friction via the interfacial shear stress.

The presence of water in the stratum corneum has been linked to its friction behaviour [6,7,21,28,30–32]. Typically, water increases the friction through softening and plasticising of the skin [28], with the increased contact size leading to increased friction as indicated in Eq. 1. The presence of lipids on the skin surface has also been shown to have an effect on the friction in skin contacts [10,12,33,34], but the exact relationships have not been established. Cua [10] investigated the relationship between friction and the skin surface lipid content for eleven anatomical locations and only found a weak correlation for the post-auricular area and the forehead. Gupta [33] found a moderate correlation between the amount of sebum on the skin and the observed friction but did not elaborate on the methods they employed to establish these sebum levels. Pailler-Mattei [34] showed that the lipid film on the skin surface influences the adhesion properties, with skin in the 'normal' state showing significant adhesion, which was strongly reduced after cleaning or removal of the lipids from the skin.

1.2. FTIR spectroscopy of skin

Spectroscopy techniques including FTIR have been widely used in dermatological and cosmetic investigations, see for instance [22–26]. Fig. 1 (a) shows a typical FTIR spectrum for in-vivo skin obtained using an Attenuated Total Reflectance (ATR) crystal, as measured on one of our volunteers. A complete overview of the peaks in the skin FTIR response, as well as their physical interpretation was provided by Lucassen [26]. In Fig. 1 (a) the bands relevant to the frictional behaviour of the skin are indicated, these will be discussed in more detail below.

There appears to be no clear consensus in literature on the best method to analyse FTIR spectra obtained on skin. Lucassen et al. [26] deconvoluted the FTIR spectrum by fitting Gaussian bands using a nonlinear least-squares search method to determine the location, height and width of the various bands. A mathematical expression for the Gaussian bands is provided by Eq. 2:

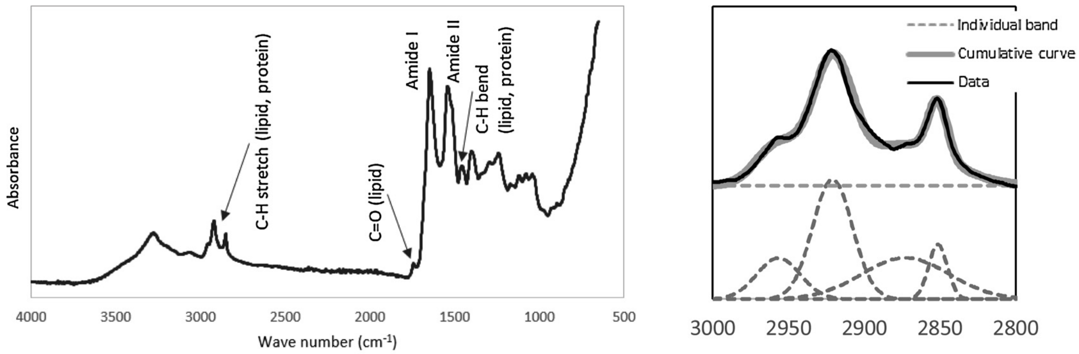
$$I_i(x) = A_i \bullet exp\{-[(x - \Omega_i)/\Gamma_i]^2\} \quad (2)$$

In which I the absorbance, A the amplitude, Ω the centre frequency, Γ the width or standard deviation of the band and x the wave number or frequency, with i representing the various bands.

When the skin is pressed onto the ATR crystal with an increased force, the contact area between skin and crystal is increased, manifesting itself in a vertical shift of the entire spectrum. This can therefore be accounted for by adjusting the baseline. Fig. 1 (b) illustrates the procedure to quantify the spectral peaks in the CH_2 asymmetric stretch range at 2920 cm^{-1}. The figure shows the measured spectrum in a black solid line, the deconvolution into individual peaks and a baseline (dotted grey lines) as well as the reconstituted superposed curves (grey solid lines).

1.3. Bands in the FTIR spectrum that relate to the frictional response of the skin

Gloor et al. employed infrared spectroscopy to study the effect of surface lipids on the water content of the epidermis [22]. They defined a '*moisture factor*' by comparing the height of the Amide I peak at



(a) Typical skin IR spectrum measured in the 4000 cm-1-650 cm-1 range.

(b) Deconvolution of the FTIR signal using Lucassen's approach [26].

Fig. 1. FTIR spectrum of in vivo skin.

1645 cm^{-1} to the height of the Amide II peak at 1545 cm^{-1}. This moisture factor is based on the concept that the height of the Amide I peak is affected by water through the H_2O-bending band at 1640 cm^{-1}, whilst the Amide II peak is unaffected by any water in the skin [22]. Potts et al. quantify the water concentration of the stratum corneum by computing the area under the 2100 cm^{-1} range, normalised by the height of the baseline between the (empirically selected) upper and lower limits of 1900 to 2300 cm^{-1} [24]. This method was also employed by Bommannan et al. [23], who used FTIR to examine the barrier function of the stratum corneum after repeated tape stripping. However, Lucassen states that the shape of the 2100 cm^{-1} band is obscured due to the high intensity of the spectrum at 1640 cm^{-1} and additionally that this peak is only observed after several minutes of contact between the skin and the ATR crystal [26]. As described later in this paper, our FTIR measurements were performed directly after initiating the contact between the forearm and the ATR crystal and indeed no peak was observed at 2100 cm^{-1}, whilst the measured absorbance in this range was very low compared to other regions in the spectra.

Bommannan further assessed the hydration of the skin using the frequency shifts of the Amide I and Amide II peaks and quantified the relative lipid content by analysing the CH_2 asymmetric stretching absorbance between 2945 and 2875 cm^{-1}. The asymmetric stretch peak at 2920 cm^{-1} has been related to lipid mobility and lipid disorder, which in bio-membrane studies is referred to as the lipid fluidity or the reciprocal of the viscosity. Knutson et al. showed using FTIR spectra on hairless mouse stratum corneum that an increased fluidity of the lipid layer (and thus a reduced viscosity) would manifest itself as a broadening of the 2920 cm^{-1} peak [35].

Prasch et al. [25] studied the effect of cosmetic products on the skin and defined a moisture factor and several factors related to '*skin greasiness*' in terms of lipids, esters and fatty acids. Similar to the work of Gloor [22], the moisture factor was defined as the ratio between the Amide I and Amide II bands. Greasiness of the skin was related to the C–H bending of lipids ($1450-1455$ cm^{-1}), the free fatty acid absorption band ($1690-1720$ cm^{-1}) and the ester absorption band ($1720-1790$ cm^{-1}). The specific greasiness parameters defined by Gloor were (i) the ratio between the fatty acid absorption and the ester absorption, (ii) the height of the total combined fatty acid and ester absorption band between 1690 and 1790 cm^{-1}, normalised with respect to the height of the Amide I band and (iii) the area of the $1450-1455$ cm^{-1} peak as representative for the amount of lipids on the surface. This area can be calculated by taking the integral of the absorbance $I(x)$ for the deconvoluted peak as calculated from eq. (2) over a total interval of $6 \cdot \Gamma_{1455}$ around the peak centre frequency Ω_{1455}. To account for variations in the contact area between the skin and the ATR crystal, this peak area is normalised with respect to the area under the baseline of the peak over the same interval, as explained in more detail by Bomannan [23].

Summarising, the parameters of interest are divided in three categories:

Greasiness parameters:

- Normalized area of 2920 cm^{-1}: measure for the amount of fatty acids on the skin [23].
- Width of the 2920 cm^{-1} band: measure for the disorder of the fatty acids, which is correlated to the reciprocal of their viscosity.
- Normalized area of 1740 cm^{-1} peak: measure for the amount of esters on the skin [25].
- Normalized area of 1450–1455 cm^{-1} peak: measure for the amount of lipids on the skin [25].

Moisture parameters:

- Amide I: area under curve $1700-1600$ cm^{-1}: the Amide I band includes 1677 cm^{-1}, 1650 cm^{-1} and 1640 cm^{-1} and is affected by water [22,25,26],
- Amide II: area under the 1545 cm^{-1} peak: the Amide II peak is not affected by water and can therefore be used to normalise the Amide I peak.
- 1585 cm^{-1}: this peak refers to a C=C stretch and partially overlaps with the Amide I peak, so needs to be subtracted from the Amide I peak.

Contact area parameter:

- The level of the baseline of the measured curve is a measure for the amount of contact between the skin and the ATR crystal [23]. Fluctuations in contact area between the skin and the ATR crystal are inevitable in in-vivo investigations, due to variations in contact force and skin properties between subjects, and these can be accounted for by adjusting the baseline.

In this work we aim to investigate the use of infrared spectroscopy techniques to identify and explain the interpersonal differences that are commonly observed in frictional behaviour of the skin.

2. Methods

In vivo skin friction experiments and in vivo FTIR measurements were performed on the volar forearms of fifteen volunteers, after which the results were analysed and compared. The Medical Ethical Review Committee Twente (METC) in Enschede, the Netherlands waived the requirement for ethical approval for this study and the trial has been registered in the Dutch Trial Register under NTR6697.

2.1. Infrared spectrometry

Spectra were obtained using an FTIR spectrometer (Spectrum 100 series, Perkin Elmer, Waltham, USA). The system was equipped with an ATR crystal which enables direct measurement on in vivo skin. Spectra were collected over a range of wavelengths from 4000 to 650 cm^{-1} with a resolution of 1 cm^{-1}. At these wavelengths, the infrared light penetrates the skin to a depth between 0.25 μm and 1 μm, depending on the wave number. Taking into account the thickness of the stratum corneum, which is about 15 μm [36], means that the obtained spectra relate to the characteristics of the stratum corneum only.

The volunteers participating in this study were asked to press their arm firmly against the ATR crystal, after which the infrared measurement was taken. The time required to perform an FTIR measurement was approximately five seconds. The additional hydration of the skin due to occlusion during this period was limited and can be ignored, as occlusion affects skin on a time-scale of minutes [37]. Additionally, the diameter of the ATR crystal was much smaller than the contact area of the friction measurement and therefore the friction results would not be significantly affected. The transferred amount of sebum from the skin to the ATR crystal was assessed by taking an additional FTIR measurement after removing the arm. In all cases neglectable absorption values were measured, showing minimal transfer of sebum onto the ATR crystal. During each FTIR measurement, five spectra were measured and averaged for each volunteer, resulting in a spectrum as illustrated in Fig. 1. The least squares search method as described by Lucassen [26] (Eq. 2) was used to extract the location (Ω_i), the amplitude (A_i) and the bandwidth (Γ_i) for each peak.

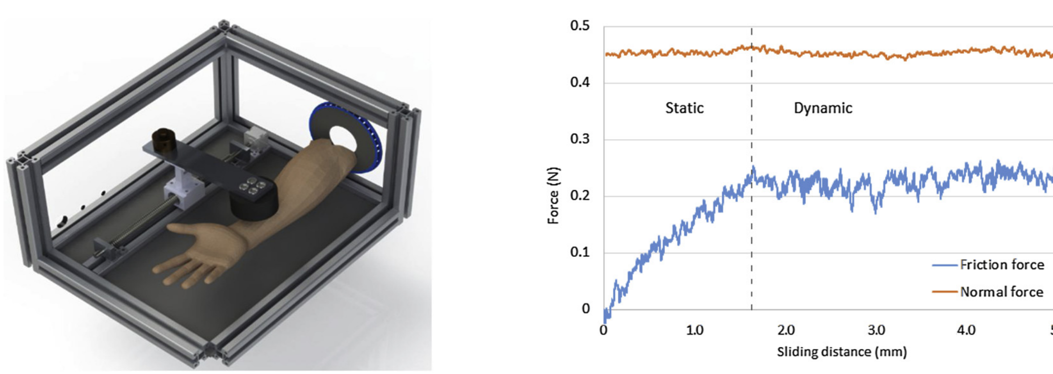
2.2. Measuring the static friction or shear response of skin

The set-up illustrated in Fig. 2 was used for performing the static friction measurements between a textile specimen and the volar forearm for each participant in this study. The employed set-up has been discussed in more detail in [38]. A new textile specimen was mounted onto a six-axis force transducer (Gamma, ATI Industrial Automation, Apex, USA) for each participant. A normal load of 0.45 N was applied to the contact using a dead-weight on a balancing arm, resulting in a calculated contact pressure of 10 kPa. This value is representative for the pressure in a range of skin-product interactions, including a person in a seated position [39,40], the interaction between a face mask and the bridge of the nose [41] and the interaction between a limb prosthetic and the remaining part of the extremity [42]. Following application of the normal load, the shear loading of the skin was introduced by slowly moving the force transducer at a calibrated velocity of 200 $\mu m{\cdot}s^{-1}$ along the distal – proximal direction using the motor driven spindle.

The friction measurements were performed under room conditions (22 °C and 50 % RH). Fig. 2 (b) shows the typical measured force signals, the applied load (orange line) which is fairly constant throughout the duration of the test, and the friction force (blue line) which slowly increases during the 'static phase', i.e. when the probe sticks to the skin and there is no macroscopic sliding, to a more or less constant value during the dynamic phase when the probe slides against the skin. For many engineering materials the transition from static to dynamic friction is characterised by a sharp spike in the measured friction signal that defines the maximum static friction. This spike is not necessarily observed for soft materials such as human skin. The onset of sliding is also characterised by a clearly identifiable peak in the first and second time-derivatives of the measured friction force signal. In this work the initiation of full sliding motion was defined as the spike in the second time-derivative of the friction force and the peak static friction force was obtained by taking the maximum friction force signal in the period of 0.2 s immediately around this onset of motion. The total displacement of the probe was set to 10 mm, which is sufficient to initiate full sliding between the textile specimen and the skin. This value has previously [38] been established as a pragmatic compromise between the total duration of the experiment (and thus the burden on the participating volunteers) and the ease of identifying the maximum static friction force at the onset of full motion. Using this setup a large number of measurements were previously performed on a single volunteer, showing a high repeatability and a very small variation of +/− 0.03 for the static friction coefficients obtained in the same environment as in this study [38].

2.3. Friction specimens

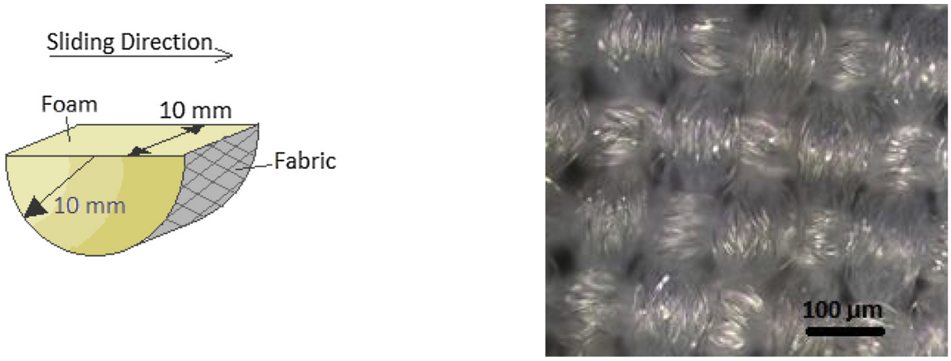
Specimens comprise a semi-cylindrically shaped foam rubber covered by a plain weave polyester fabric layer with a diameter of 20 mm and a width of 10 mm as schematically illustrated in Fig. 3(a). Polyester fabrics are commonly used in products that are in direct contact with skin such as bed sheets or clothing. The fabric had a plain weave with an approximate fibre diameter of 5 μm and a weave size of 180 μm and was purchased from a fabric shop in Enschede, The Netherlands. A microscope image of the textile surface is shown in Fig. 3(b). A new, clean specimen was used for each participant.



(a) Illustration of the friction measurement setup.

(b) Typical force signals obtained with the friction setup. The blue line indicates the friction force and the orange line indicates the normal force.

Fig. 2. The experimental setup employed in this study and a typical measurement result. A more elaborate explanation of setup can be obtained from [38].



(a) Schematic illustration.

(b) Microscopy image of the textile surface.

Fig. 3. The specimens used for the friction measurements.

2.4. Participants

Initially, a total of sixteen healthy volunteers were included in the study. Inclusion criteria included an age between 20 and 35 years and no history of skin disease. The in vivo ATR FTIR measurements and friction measurements were performed on approximately the same location on the volar forearm of each of the participants. Each FTIR measurement was followed by the friction experiment within a time of 5 min. The skin was not prepared or cleaned in any way immediately prior to the experimental programme and participants were asked to confirm that the last time they cleaned or washed the skin was at least one hour prior to the experiments. Participants were also instructed in advance to not use any topical creams to ensure the skin was in a 'natural state'.

During the measurements it was observed that one subject had an extremely hairy volar forearm, disrupting both the friction experiments and the infrared measurements obtained on this individual. The friction contact was essentially a hair-textile interaction whilst the infrared spectrum measured on this subject was considerably different from the other fifteen subjects, so it was decided to remove this volunteer from the study and the results will not be reported or used in the analysis. The presented results and conclusions are therefore based on the results obtained on fifteen participating volunteers.

2.5. Summary of the experimental setup

The experimental setup used in this investigation can be summarised as:

- Number of volunteers included in the analysis: 15.
- Inclusion criteria: Healthy, Age 20–35 years, No history of skin trauma or problems.
- FTIR spectrum measured: 4000 – 650 cm^{-1}, with 1 cm^{-1} resolution.
- FTIR bands of interest [cm^{-1}]: 2920, 1740, 1677, 1650, 1640, 1585, 1545, 1455.
- Contact: In vivo skin against fabric on a foam base.
- Skin condition: natural, no pre-trial cleaning or application of topical creams.
- Normal load applied in the friction measurement: 0.45 N.
- Approximate contact pressure: 10 kPa.
- Sliding speed: 200 µm·s^{-1}.

3. Results

Utilising the methods described previously, the FTIR spectra and the coefficient friction were measured in-vivo on a total of 15 volunteers. Fig. 4(a) shows the friction coefficient obtained for each of the participants. The figure clearly shows the variation in friction response between different subjects, despite keeping the conditions constant during the experiments. The average coefficient of friction is 0.76, with a standard deviation of 0.19. The lowest value is 0.47 while the highest value is 1.08. These results confirm the strong effect of interpersonal differences on the friction response of the skin.

The measured FTIR spectra for the fifteen participants are shown in Fig. 4(b), where the colours of the spectra are matched to the bars for the friction results presented in Fig. 4(a). The spectra show some variation, but there is no immediately obvious trend that relates the various spectra and the friction values. A more detailed analysis of the spectra was obtained using Lucassen's least squares search method (eq. 2) for the bands that are of interest with respect to the frictional behaviour of skin. These results are listed in Table 1, with the width (Γ_i) and the amplitude of the peaks (A_i) in the grey and the white coloured cells, respectively.

4. Discussion

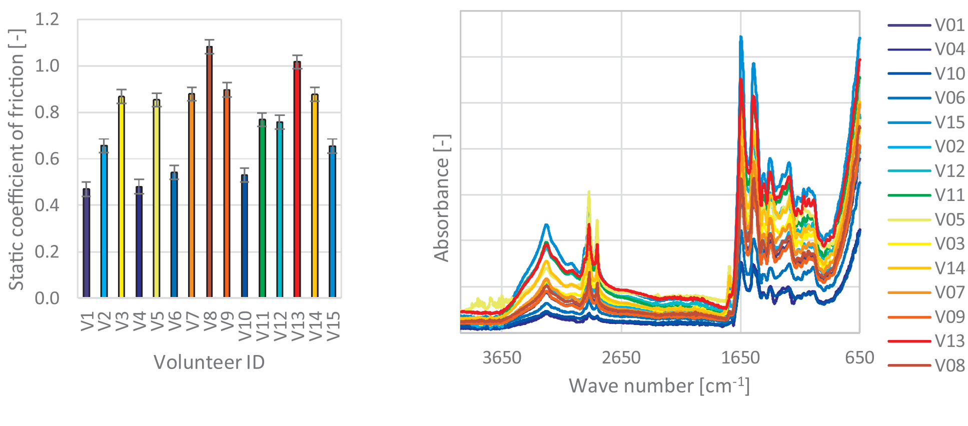
As described in the introduction to this paper, based on literature we defined a range of FTIR parameters that may relate to the friction behaviour of the skin. These included four skin greasiness parameters, relating to the quantity and disorder of fatty acids, the quantity of esters and the quantity of lipids. Additionally, a skin moisture parameter was defined based on the ratio of the amide I and II peaks.

4.1. Friction with respect to surface lipids

The area of three distinctive bands in the FTIR spectrum relate to the lipids on the surface: the total quantity of lipids is represented by the CH_3 deformation peak at 1455 cm^{-1}, the quantity of esters relates to the C=O stretch at 1740 cm^{-1} and the width and area of the CH_2 asymmetry peak at 2920 cm^{-1} represent the disorder and quantity of fatty acids on the surface, respectively. The graphs in Fig. 5 plot the relationships between the total quantity of lipids and the quantity of fatty acids, with the measured coefficient of friction. From the distribution of the data points it is clear that there is no significant correlation between the coefficient of friction and these characteristics.

These findings indicate that the quantity of lipids on the skin is not directly related to the measured coefficient of friction.

Bommannan states that the width of the CH_2 asymmetry band at 2920 cm^{-1} (Γ_{2920}) correlates with the lipid disorder, which in the context of the skin barrier function is the lipid's resistance to deformation due to a mechanical stress, meaning this band provides some indication for the viscosity of the lipids. The penetration depth of the infrared beam into the skin at a wave number of 2920 cm^{-1} is approximately 0.25 µm [14], which is well below the 1 µm thickness of single corneocytes [43], suggesting that this band relates to surface lipids rather than intercellular lipids. Fig. 6 shows the measured coefficient of

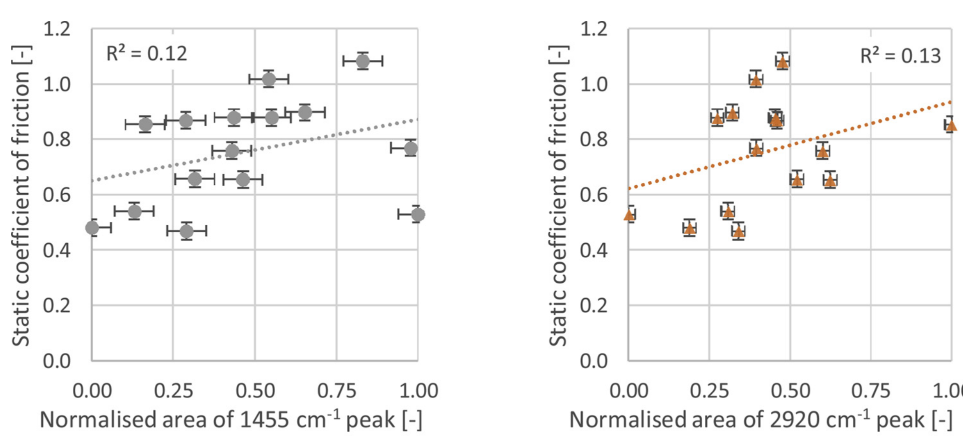


(a) In-vivo static friction coefficients. *(b) In-vivo FTIR spectra.*

Fig. 4. Friction and FTIR results obtained on the 15 volunters. The colours of the bars in (a) and the spectra in (b) correspond to the specific volunteer. The error bars indicate the standard deviation of the friction measurement as obtained in [38] (n = 96).

Table 1
Characteristics of the various spectral peaks. The values in the white boxes show the amplitude of the peaks, the values in the grey boxes show the width of the peaks.

	Base-line	2920 cm^{-1}		1740 cm^{-1}		1677 cm^{-1}		1650 cm^{-1}		1640 cm^{-1}		1585 cm^{-1}		1545 cm^{-1}		1455 cm^{-1}	
	height	width	height	width	height	width	height	width	height	width	height	width	height	width	height	width	height
V1	0.011	18.0	0.009	17.1	0.003	0.5	0.000	40.2	0.038	22.7	0.017	37.2	0.027	19.5	0.029	18.0	0.008
V2	0.014	18.6	0.014	16.8	0.006	1.7	0.000	41.7	0.038	24.2	0.021	37.3	0.031	19.3	0.032	19.5	0.011
V3	0.015	18.1	0.015	21.9	0.009	3.4	0.000	44.3	0.037	26.6	0.026	35.8	0.036	18.8	0.030	17.1	0.012
V4	0.005	18.8	0.003	20.8	0.005	5.0	0.002	35.5	0.012	32.7	0.015	32.8	0.013	19.8	0.017	9.0	0.001
V5	0.020	18.1	0.035	16.5	0.014	0.2	0.000	42.3	0.044	24.0	0.023	34.0	0.031	17.9	0.026	14.8	0.014
V6	0.008	18.2	0.006	16.5	0.002	0.1	0.000	40.2	0.025	23.3	0.014	36.6	0.019	19.3	0.023	15.6	0.004
V7	0.013	17.6	0.001	13.9	0.002	3.9	0.000	39.1	0.050	21.5	0.021	40.0	0.035	18.8	0.033	20.7	0.012
V8	0.012	17.4	0.013	16.1	0.003	4.5	0.001	39.8	0.039	23.4	0.021	36.8	0.031	17.5	0.022	27.1	0.017
V9	0.010	17.8	0.008	14.3	0.003	4.8	0.000	39.4	0.038	21.7	0.018	41.3	0.025	18.2	0.024	23.0	0.015
V10	0.005	18.0	0.002	17.2	0.001	0.000	0.000	40.0	0.017	22.9	0.008	40.1	0.014	18.1	0.012	30.0	0.011
V11	0.020	18.2	0.018	19.2	0.008	4.0	0.001	42.0	0.062	22.5	0.033	39.7	0.049	18.5	0.044	26.0	0.030
V12	0.020	18.1	0.024	16.7	0.005	4.7	0.001	52.0	0.039	28.9	0.040	32.3	0.041	19.3	0.034	18.6	0.019
V13	0.023	18.0	0.021	17.6	0.005	4.2	0.000	43.2	0.059	25.0	0.036	37.4	0.052	17.9	0.039	21.3	0.025
V14	0.017	17.9	0.017	22.6	0.015	3.5	0.000	40.3	0.056	22.0	0.027	40.0	0.040	17.1	0.028	20.1	0.022
V15	0.024	18.4	0.028	16.6	0.009	3.5	0.001	42.7	0.069	23.7	0.045	38.0	0.055	19.3	0.059	21.0	0.022

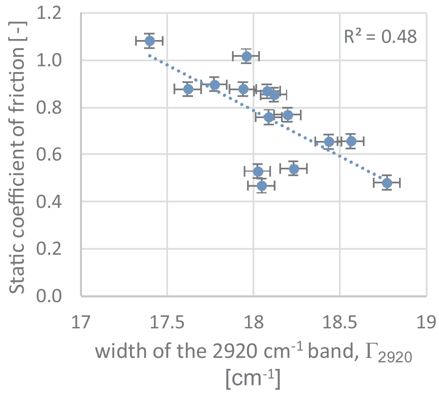


(a) *(b)*

Fig. 5. Observed correlations between (a) the total quantity of lipids on the skin surface and (b) the quantity of fatty acids on the skin. Vertical error bars indicate the standard deviation of the friction measurements (n = 96), whilst horizontal error bars indicate the standard deviation from five separately taken spectra.

friction plotted as a function of the width of the 2920 cm^{-1} band. The results indicate a decrease of the coefficient of friction with increasing bandwidth, meaning the friction decreases with decreasing viscosity of the lipids.

From Fig. 5 and Fig. 6(a) it can be concluded that the frictional behaviour of the skin is not determined by the amount of lipids on the skin, but rather by their mechanical properties, as the width of the 2920 cm^{-1} peak correlates with the reciprocal of the viscosity. It needs to be emphasised that these results refer to untreated skin, i.e. skin in its 'natural state' and are therefore not directly contradicting the results obtained by Pailler-Mattei [34] who compared skin that was carefully cleaned to untreated skin in its natural state and found a distinct effect



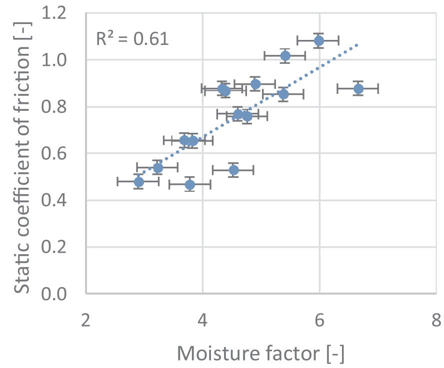


Fig. 6. Observed correlations between (a) the disorder of the fatty acids on the skin surface and (b) the moisture factor of the skin. The vertical error bars indicate the standard deviation for the friction experiments (n = 96), whilst the horizontal error bars indicate the standard deviation from five separately taken spectra.

of the amount of lipids.

4.2. Friction with respect to moisture

The moisture factor was defined as the ratio between the Amide I and Amide II bands [22,25]. Fig. 6(b) shows the measured friction plotted against this moisture factor for the fifteen subjects and shows a positive correlation between the two parameters. This confirms that moisture content and friction response are strongly correlated: the higher the moisture content in the skin, the higher the coefficient of friction. This behaviour has been attributed to plasticising and softening of the stratum corneum [28].

In contrast to results described in literature for large groups of subjects, in which no direct relationship between skin friction and moisture [6] is found, the presented results show a linear correlation with an acceptable quality ($R^2 = 0.61$) for measurements on the entire group of subjects (n = 15).

5. Conclusions

In this work we presented the results of friction measurements on in vivo human skin and related these to FTIR spectra obtained on the same patch of skin. Figs. 5 and 6 showed that there is a correlation between the properties of the skin lipids and the friction as well as between the moisture content of the stratum corneum and the friction, respectively, but that this relationship is more complex than a simple linear correlation. The obtained values for the coefficient of determination (R^2) of the linear curve fits are too low to provide sufficient confidence in any predictive models that would be based on these data points. Indeed, moisture and lipids are only indirectly affecting the two components in Eq.1: a reduced moisture content of the stratum corneum increases the stiffness of the skin, which in turn reduces friction through the reduced contact area, but those relationships are markedly nonlinear.

The following conclusions can be drawn:

- Static friction values, measured on several people by pressing and sliding a textile specimen against their skin, show a large spread, even when all other test parameters are carefully controlled and kept constant. This variation between people is much larger than would be expected based on the repeatability of the test.
- FTIR provides a direct quantified measure of skin moisture and lipid characteristics, which provides a step-change in terms of ease, quantification and accuracy compared to the current practice in the field of tribology of using capacitive measurements and the use of absorbent tape.
- The moisture content of the stratum corneum is a main parameter affecting friction. The Moisture Factor, defined as the ratio of the Amide I and Amide II bands provides a positive correlation with the friction.
- The viscosity of the skin surface lipids correlates to the friction behaviour of the skin. The narrower the width of the 2920 cm^{-1} band, the higher the viscosity and the higher the resulting friction.
- For skin in its natural state, the amount of lipids on the skin appears not to be relevant for the friction in skin-object interactions.

The presented relationships between the resulting friction in the skin-object interface and both the lipid viscosity characteristics and the moisture level in the stratum corneum provide interesting insights and could form the basis of a clinical tool that aims to identify people with skin that has inherently elevated friction and who could therefore be at increased risk of developing shear induced skin injury.

CRediT authorship contribution statement

M. Klaassen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **E.G. De Vries:** Conceptualization, Data curation, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **M.A. Masen:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] D. Dowson, A tribological day, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 223 (March 3) (2009) 261–273.
[2] P. Laszczak, M. McGrath, J. Tang, J. Gao, L. Jiang, D.L. Bader, D. Moser, S. Zahedi, A pressure and shear sensor system for stress measurement at lower limb residuum/socket interface, Med. Eng. Phys. 38 (7) (2016) 695–700.
[3] L.A. De Wert, D.L. Bader, C.W.J. Oomens, L. Schoonhoven, M. Poeze, N.D. Bouvy, A new method to evaluate the effects of shear on the skin, Wound Repair Regen. 23 (6) (2015) 885–890.
[4] C. Guerra, C.J. Schwartz, Development of a Synthetic Skin Simulant Platform for the

Investigation of Dermal Blistering Mechanics, Tribol. Lett. 44 (2) (2011) 223.
[5] S. Derler, A. Rao, P. Ballistreri, R. Huber, A. Scheel-Sailer, R.M. Rossi, Medical textiles with low friction for decubitus prevention, Tribol. Int. 46 (1) (2012) 208–214.
[6] N.K. Veijgen, M.A. Masen, E. van der Heide, Relating friction on the human skin to the hydration and temperature of the skin, Tribol. Lett. 49 (1) (2012) 251–262.
[7] L.C. Gerhardt, V. Strässle, A. Lenz, N.D. Spencer, S. Derler, Influence of epidermal hydration on the friction of human skin against textiles, J. R. Soc. Interface 5 (28) (2008) 1317–1328.
[8] M. Egawa, M. Oguri, T. Hirao, M. Takahashi, M. Miyakawa, The evaluation of skin friction using a frictional feel analyzer, Skin Res. Technol. 8 (1) (2002) 41–51.
[9] N.K. Veijgen, M.A. Masen, E. van der Heide, Variables influencing the frictional behaviour of in vivo human skin, J. Mech. Behav. Biomed. Mater. 28 (2013) 448–461.
[10] A.B. Cua, K.P. Wilhelm, H.I. Maibach, Skin surface lipid and skin friction: relation to age, sex and anatomical region, Skin Pharmacol. Physiol. 8 (5) (1995) 246–251.
[11] A.B. Cua, K.P. Wilhelm, H.I. Maibach, Friction Properties of human skin: relation to age, sex and anatomical region, stratum corneum hydration and trensepidermal water loss, Skin Pharmacol. Physiol. 123 (4) (1990) 473–479.
[12] L.C. Gerhardt, A. Lenz, N.D. Spencer, T. Münzer, S. Derler, Skin-textile friction and skin elasticity in young and aged persons, Skin Res. Technol. 15 (3) (2009) 288–298.
[13] R.K. Sivamani, G.C. Wu, N.V. Gitis, H.I. Maibach, Tribological testing of skin products: gender, age, andethnicity on the volar forearm, Skin Res. Technol. 9 (2003) 299–305.
[14] N.K. Veijgen, E. van der Heide, M.A. Masen, A multivariable model for predicting the frictional behaviour and hydration of the human skin, Skin Res. Technol. 19 (3) (2013) 330–338.
[15] A.B. Cua, K.P. Wilhelm, H.I. Maibach, Elastic properties of human skin: relation to age, sex, and anatomical region, Arch. Dermatol. Res. 282 (5) (1990) 283–288.
[16] S. Derler, R. Rossi, G.-M. Rotaru, Understanding the variation of friction coefficients of human skin as a function of skin hydration and interfacial water films, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. (2014).
[17] J. van Kuilenburg, M.A. Masen, E. van der Heide, Contact modelling of human skin: What value to use for the modulus of elasticity? Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 227 (4) (2012) 349–361.
[18] S. Derler, L.C. Gerhardt, Tribology of skin: review and analysis of experimental results for the friction coefficient of human skin, Tribol. Lett. 45 (1) (2011) 1–27.
[19] D. Batisse, F. Giron, J.L. Lévêque, Capacitance imaging of the skin surface, Skin Res. Technol. 12 (2) (2006) 99–104.
[20] A. Pagnoni, I. Sadiq, T. Stoudemayer, A. Kligman, Image analysis of D-squames, sebutapes and of cyanoacrylate follicular biopsies, Bioengineering of the Skin: Skin Imaging and Analysis, (2006).
[21] M. Kwiatkowska, S.E. Franklin, C.P. Hendriks, K. Kwiatkowski, Friction and deformation behaviour of human skin, Wear 267 (5–8) (2009) 1264–1273.
[22] M. Gloor, U. Willebrandt, G. Thomer, W. Kupferschmid, Water content of the horney layer and skin surface lipids, Arch. Dermatol. Res. 268 (1980) 221–223.
[23] D. Bommannan, R.O. Potts, R.H. Guy, Examination of stratum corneum barrier function in vivo by infrared spectroscopy, J. Invest. Dermatol. 95 (4) (1990) 403–408.
[24] R.O. Potts, Stratum corneum hydration: experimental techniques and interpretations of results, J. Cosmet. Sci. 37 (1986) 9–33.
[25] T. Prasch, G. Knübel, K. Schmidt-Fonk, S. Ortanderl, S. Nieveler, T. Förster, Infrared spectroscopy of the skin: influencing the stratum corneum with Cosmet. Products, Int. J. Cosmet. Sci. 22 (2000) 371–383.
[26] G.W. Lucassen, G.N. van Veen, J.A. Jansen, Band analysis of hydrated human skin stratum corneum attenuated total reflectance fourier transform infrared spectra in vivo, J. Biomed. Opt. 3 (3) (1998) 267–280.
[27] G.W. Stachowiak, A.W. Batchelor, Engineering Tribology (Fourth Edition), (2006).
[28] M.J. Adams, B.J. Briscoe, S.A. Johnson, Friction and lubrication of human skin, Tribol. Lett. 26 (3) (2007) 239–253.
[29] S. Derler, G.M. Rotaru, W. Ke, L. El Issawi-Frischknecht, P. Kellenberger, A. Scheel-Sailer, R.M. Rossi, Microscopic contact area and friction between medical textiles and skin, J. Mech. Behav. Biomed. Mater. 38 (2014) 114–125.
[30] S. Tomlinson, R. Lewis, X. Liu, C. Texier, M. Carré, Understanding the friction mechanisms between the human finger and flat contacting surfaces in moist conditions, Tribol. Lett. 41 (2011) 283–294.
[31] C.P. Hendriks, S.E. Franklin, Influence of surface roughness, material and climate conditions on the friction of human skin, Tribol. Lett. 37 (2) (2009) 361–373.
[32] M.A. Masen, A systems based experimental approach to tactile friction, J. Mech. Behav. Biomed. Mater. 4 (8) (2011) 1620–1626.
[33] A.B. Gupta, B. Haldar, M. Bhattacharya, A simple device for measuring skin friction, Indian J. Dermatol. 40 (3) (1995) 116–121.
[34] C. Pailler-Mattei, S. Nicoli, F. Pirot, R. Vargiolu, H. Zahouani, A new approach to describe the skin surface physical properties in vivo, Colloids Surf. B Biointerfaces 68 (2) (2009) 200–206.
[35] K. Knutson, S.L. Krill, W.J. Lambert, W.I. Higuchi, Physicochemical aspects of transdermal permeation, J. Control. Release 6 (1987) 59–74.
[36] K.A. Holbrook, G.F. Odland, Regional differences in the thickness (cell layers) of the human stratum corneum: an ultrastructural analysis, J. Invest. Dermatol. 62 (4) (1974) 415–422.
[37] S.E. Franklin, J. Baranowska, C.P. Hendriks, J. Piwowarczyk, M. Nachman, Comparison of the friction behavior of occluded human skin and synthetic skin in dry and moist conditions, Tribol. Trans. 60 (5) (2017) 861–872.
[38] M. Klaassen, D.J. Schipper, M.A. Masen, Influence of the relative humidity and the temperature on the in-vivo friction behaviour of human skin, Biotribology 6 (2016) 21–28.
[39] E. Linder-Ganz, N. Shabshin, Y. Itzchak, A. Gefen, Assessment of mechanical conditions in sub-dermal tissues during sitting: a combined experimental-MRI and finite element approach, J. Biomech. 40-7 (2007) 1443–1454.
[40] C.J. Boyle, D. Carpanen, T. Pandelani, C.A. Higgins, M.A. Masen, S.D. Masouros, Lateral pressure equalisation as a principle for designing support surfaces to prevent deep tissue pressure ulcers, PLoS One 15 (2020) e0227064.
[41] A.-K. Brill, R. Pickersgill, M. Moghal, M.J. Morrell, A.K. Simonds, Mask pressure effects on the nasal bridge during short-term noninvasive ventilation, ERJ Open Res. 4 (2018) 00168–02017.
[42] J.C.H. Goh, P.V.S. Lee, S.Y. Chong, Stump/socket pressure profiles of the pressure cast prosthetic socket, Clin. Biomech. 18-3 (2003) 237–243.
[43] Z. Ya-Xian, T. Suetake, H. Tagami, Number of cell layers of the stratum corneum in normal skin - relationship to the anatomical location on the body, age, sex and physical parameters, Arch. Dermatol. Res. 291 (10) (1999) 555–559.